

# Phase Calibration for the Block I VLBI System

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*Very Long Baseline Interferometry (VLBI) in the DSN provides support for spacecraft navigation, earth orientation measurements, and synchronization of network time and frequency standards. An improved method for calibrating instrumental phase shifts has recently been implemented as a computer program in the Block I system. The new calibration program, called PRECAL, performs calibrations over intervals as small as 0.4 seconds and greatly reduces the amount of computer processing required to perform phase calibration.*

## I. Introduction

VLBI is a method of measuring the difference in arrival time of a radio signal at two widely separated antennas in order to determine other parameters of the observation. Radio signals from an extragalactic source (or from a spacecraft) are recorded simultaneously at two antennas on the earth's surface. Because of a difference in ray paths, the signal's arrival is delayed at one antenna relative to the other. This delay and its time derivative are of interest because they are observable parameters of a physical system which includes earth orientation, source location, and station clock parameters that cannot be observed directly. When a comprehensive mathematical model of this physical system is fitted to the delay parameters derived from VLBI observations, accurate estimates can be obtained for parameters such as the instantaneous rotation angle of the earth (UT1), polar motion, source positions, and the difference in clock epochs and rates at the two stations (Refs. 1-3).

The measured delay includes the delays experienced by the signals while passing through the station instrumentation. Phase calibration removes these components of the delay. Without phase calibration, the delays obtained using the bandwidth synthesis procedure (see below) contain unknown offsets due to frequency-dependent instrumental phase shifts. These instrumental delay offsets are indistinguishable from epoch differences between the station clocks and must be eliminated before absolute clock offsets can be measured.

Another benefit of phase calibration is that bandwidth synthesis delay ambiguities may be resolved independently for each source, using the simpler and more reliable process of single observation ambiguity resolution (Ref. 4). Without phase calibration, the resolution of BWS phase ambiguities is complicated by the presence of different instrumental phase shifts in different channels.

## II. Data Acquisition

In Fig. 1 the radio signal from a source is received at two DSN antennas. Both antennas observe one or more sources in an identical, simultaneous sequence. During each observation, both receiving stations repeatedly cycle through several 250-kHz bandwidth channels in unison to record data from several different frequencies for bandwidth synthesis. The radio data are 1-bit sampled and recorded at the Nyquist rate of 500,000 bits per second. After they are collected, the VLBI data from both stations are replayed over the Ground Communication Facility (GCF) wide band data (WBD) lines to the VLBI Processor Subsystem (VPS) at JPL and are filed on the VPS disks for processing.

## III. Cross Correlation

The two VLBI data streams are cross-correlated by the Block I VLBI Correlator Hardware Assembly under control of the VLBI Correlation Operational Program (VCOROP) (Ref. 5) as shown in Fig. 2. The correlation operation is performed simultaneously for each of 16 discrete time offsets, or "lags", between the streams. The lags are spaced at 2-microsecond intervals, which represent shifts of one bit in the 500,000-bps data streams.

Correlation reduces the data in each "correlation interval" to one pair of sine and cosine correlation sums per lag. During correlation the data streams are multiplied by a "fringe phase model" which counter-rotates the interferometer fringe phase to compensate for the earth's rotational doppler effect at the antennas, and the bitstream alignment is periodically shifted by one bit to offset the earth's rotational effect on the delay. The resulting "stopped fringe" correlation sums are then Fourier transformed from the lag domain to the frequency domain to obtain one complex correlation sum at each of 8 baseband frequencies for each correlation interval. The correlation and normalization sums and the correlator fringe phase model for each correlation interval are stored on the VPS disks in a file called the Post Correlation Record (PCR).

During cross correlation, as many as eight bandwidth synthesis (BWS) channels can be processed using time multiplexing. The dwell time on each channel defines a data segment that must be a multiple of 0.2 sec. The data from each channel in the multiplexing cycle are correlated over one or more correlation intervals, which must also be multiples of 0.2 sec. Data segments for a particular channel are often subdivided into two or more correlation intervals to allow for processing more than one calibration tone per channel, as explained below.

## IV. Fringe Phase

Each of the complex correlation sums can be represented by a phase and an amplitude. Phase calibration affects only the phase component of the correlation sums. Prior to phase calibration, the phases of the stopped fringe data points are given by (Ref. 4):

$$\psi_k = \omega_k (\Delta\tau_g + \tau_b + \tau_I) + \phi_I(\omega_k) + \Delta\phi_h, k = 0, 1, \dots, 15$$

where

$$\psi_k = \text{uncalibrated fringe phase at frequency } \omega_k$$

$$\omega_k = \text{baseband frequency}$$

$$\Delta\tau_g = \text{group delay residual: observed delay minus modeled delay, including delays due to geometry, media and antenna offsets}$$

$$\tau_b = \text{data recorder clock error, station 1-station 2}$$

$$\tau_I = \text{instrumental delay, station 1-station 2}$$

$$\phi_I = \text{instrumental phase shift, station 1-station 2}$$

$$\Delta\phi_h = \text{heterodyne phase residual, station 1-station 2: observed phase minus modeled phase}$$

Phase calibration removes the instrumental terms corresponding to  $\tau_b$ ,  $\tau_I$ ,  $\phi_I$  and  $\Delta\phi_h$ . The physical interpretations of these terms are shown in Fig. 3.

## V. Phase Calibration

During the data collection, monochromatic phase calibration "tones" derived from the station frequency standards are injected into the first stage maser amplifiers and superimposed on the recorded radio signals. The tones are evenly spaced across the radio spectrum in such a way that each recorded frequency channel contains two or more tones whose differences in phase and frequency can later be used to calibrate the instrumental delays that are experienced by the signals at each station. The total delay between the two VLBI data streams includes the difference in instrumental delays experienced by the VLBI data between the antenna and the recording equipment at the two stations. The PRECAL program makes use of the relationship between the recorded tone phases and the known tone frequencies to calibrate the delays experienced by the tones at each station. However, the tone delays include the "uplink", or "cable," delay  $\tau_u$ , from the tone generator to the antenna, which does not affect the VLBI data, as well as the "downlink" instrumental delay  $\tau_I$ , from the antenna to the recording equipment as shown in Fig. 3. Therefore, the instru-

mental delay effect on the fringe phase is equal to the difference in the tone delays minus the difference in the uplink delays for the two stations. In practice, PRECAL corrects the fringe phase to compensate for the difference in the tone delays while the difference in the uplink delays, which are monitored and stabilized over each set of observations, is allowed to appear as an additional clock offset between the two stations. (This offset is later removed during the parameter estimation operations.)

As the data from each correlation interval are correlated, one phase calibration tone from each station is also correlated against an appropriate tone model. This produces two complex stopped tone data points per correlation interval. The phase difference between these stopped tone phases at the two stations at frequency  $\omega_k$  is given by (Ref. 4):

$$\phi_k = \omega_k (\tau_b - \tau_c + \tau_l + \tau_u) + \phi_l + \Delta\phi_h, k = 0, 1, \dots, 15$$

where

$\phi_k$  = tone phase difference, station 1-station 2

$\omega_k$  = baseband tone frequency

$\tau_c$  = clock reference point epoch offset, station 1-station 2

$\tau_u$  = calibration signal uplink delay, station 1-station 2

The fringe phase is calibrated by subtracting the tone phase from the fringe phase to obtain:

$$\psi_k^* = \psi_k - \phi_k = \omega_k (\Delta\tau_g + \tau_c - \tau_u), k = 0, 1, \dots, 15$$

Note that cancellation of the  $\tau_b$  and  $\tau_l$  terms depends on matching the calibration tone frequencies with the fringe function baseband frequency  $\omega_k$ , while cancellation of the  $\Delta\phi_h$  terms depends on the use of the same heterodyne model for both fringe and tone phase. It is not practical to correlate a separate tone frequency for each of 16  $\omega_k$  in the Block I system. Instead, the instrumental phase is interpolated to each  $\omega_k$  before phase calibration is performed. For linear interpolation, at least two calibration frequencies are needed in each channel. (It is assumed that the Block I hardware specifications are sufficient to ensure that linear interpolation using two tones per passband is adequate for this purpose.) However, the Block I correlator correlates only one tone from each station during each correlation interval. Therefore, the multiple tones that are required for each frequency channel are obtained by correlating a different tone over each of two or more successive correlation intervals for each frequency channel. PRECAL then uses the multiple tones obtained in

this way to apply a single fringe phase correction to each such group of successive intervals from the same frequency channel.

For each group of successive correlation intervals from a given frequency channel, PRECAL approximates the tone phase at each station using a linear fit of phase against frequency for two or more tones. Any number of calibration frequencies may be used, subject to the restriction that all channels must be calibrated with the same number of frequencies.

Because only the fractional cycles of tone phase can be observed, PRECAL must rely on an independent calibration of the instrumental delay at each station to within less than one half cycle of the observed tone phase in order to resolve the integer cycle ambiguities. For a single tone in the 2000-MHz range, this would require an independent calibration of the delay to about one-fourth nanosecond, which is not feasible. However, PRECAL observes the phase and frequency differences between two or more tones from each station, thereby reducing the tone delay ambiguity to the reciprocal of the tone spacing and relaxing the independent calibration requirements proportionately (e.g., to 5  $\mu$ sec for a tone spacing of 100 kHz).

In theory, phase calibration may be performed at any point of the data analysis following cross-correlation. In the past, the phase calibration data for an entire observation lasting up to several minutes were processed separately from the fringe data using the PCAL program. After the delay parameters were estimated from the fringe data by the PHASOR program and the calibration parameters were estimated from the tone data by PCAL, a single calibration was made to the delays at the mean time of the observation.

In the new system using the program PRECAL, the phase calibration data are combined with the correlation sums prior to estimation of the delay parameters by the program PHASOR as shown in Fig. 2. In this way, the delay parameters produced by PHASOR are completely phase calibrated and the extra processing required to obtain the tone parameters and combine them with the PHASOR results is eliminated. In addition, the PRECAL calibration is performed for each correlation interval, lasting only a few tenths of a second, instead of once for an entire observation.

## VI. Calibration Algorithm

The PRECAL program verifies that the stopped tone data required for phase calibration are available, calibrates the fringe phase to remove the effects of instrumental delays, and translates the fringe data into the format expected by the PHASOR program. PRECAL operates on a PCR file produced by the correlator and creates four output files containing

reformatted data. One of these contains the calibrated fringe data while a second contains the uncalibrated data for use if calibration is unsuccessful. Two other output files receive the tone data from one station each for use in analyzing tones. These output files are created in the form expected by the tone analysis program, PCAL. A listing file that summarizes the calibration status and results is also created.

PRECAL uses the shift in phase between two or more tones of known frequency to calculate the instrumental delay at each station. Because this delay varies with both frequency and time, it must be calculated for each channel and updated periodically in time. In practice, the delay for each channel and station is computed for each correlator cycle, which is the data interval over which the correlator cycles through all of the channels and tone models. This typically corresponds to a few seconds in time, which is a sufficient updating interval for the stopped fringes and tones produced by the correlator. PRECAL's first major operation is to ensure that two or more stopped tones are available in each channel for each correlator cycle.

The sequence in which data from the different channels are recorded and correlated is specified by a phase model table in the PCR file. The corresponding sequence of tone models used for tone stopping is specified by a tone model table. PRECAL checks the phase and tone model tables to verify that two or more stopped tones are specified for each channel. To facilitate calibration, PRECAL also verifies that all channels have the same number of stopped tones.

The next task of the phase calibration operation is to obtain a priori estimates of the instrumental delays at each station, for use in resolving the tone phase ambiguities. Ideally, these estimates would be read from the station catalog, and the PRECAL program does this if the estimates are found in the catalog. If an a priori instrumental delay estimate is not found in the station catalog, PRECAL derives its own estimate as described below.

If no a priori instrumental delay estimate for a given station is found in the station catalog, tone data from the first correlator cycle of the observation are used to derive an estimate. First, the tone phase ambiguities in each channel are resolved to align the tone data between zero and one cycle of phase shift for the narrowest tone pair in the channel, and the instrumental delay is estimated from the tone phase shifts. Then, this estimated delay for each channel is used to resolve the tone phase shift ambiguities in the other channels and derive delay estimates for them. When these two steps are completed for all of the channels, the individual channel delay estimate from the first step that produced the best agreement between the estimates for the other channels in the second

step is chosen as the station a priori instrumental delay estimate. Although the instrumental delays are dispersive, the variation between channels is small compared to the magnitude of the delay, so the estimates for all channels should be in close agreement (except when they are corrupted by the presence of apparent tone delays, which are discussed below).

At present, the instrumental delays observed by tone tracking are severely corrupted by the presence of apparent tone delays which are caused by a lack of synchronization between the recorder clocks and the output pulses produced by the tone generators and are indistinguishable from  $\tau_u$ . These station-dependent apparent delays differ from the S-band channels to the X-band channels, but remain constant in each band over each observing session. However, they vary from one observing session to the next and their magnitude is known only to be a multiple of 200 ns and to be less than the reciprocal of the tone spacing (e.g., 10  $\mu$ sec for 100-kHz tone spacing). Because accurate a priori estimates cannot be made for these apparent delays (without measuring them at the stations for each set of observations), no a priori instrumental delay estimates will be entered into the station catalog until the clock-tone generator asynchronies are removed by the installation of new tone generator hardware at the stations. Prior to the installation of new tone generators (which are currently under development and are expected to be operational sometime in 1984), PRECAL'S calculation of a priori instrumental delay estimates may fail if the apparent delays in the S-band and X-band channels differ by more than one or two  $\mu$ sec, in which case no calibration will be performed. If, on the other hand, an a priori estimate can be calculated, the apparent delays will generally cause a different constant instrumental delay offset to remain in each band of channels after calibration. Therefore, the full advantage of the PRECAL method of calibration will not be realized until the new tone generators become operational.

After a priori instrumental delay estimates are determined for both stations, the fringe data from each correlator cycle are calibrated in sequence. The acceptability of the tone data is monitored by comparing the tone amplitudes against a threshold value which is calculated so that the probability of its being exceeded by noise alone is 0.001. For each station and channel in sequence, the acceptable tone data are aligned by resolving their phase shift ambiguities against the station's a priori estimate and the instrumental delay is calculated by a linear fit of tone phase against frequency. For each channel, the fitted tone phases for the two stations are used to interpolate the corresponding tone phases for each individual baseband frequency  $\omega_k$  of the frequency domain fringe data. Finally, the difference between the station's instrumental phases for each baseband frequency of each channel is subtracted from the corresponding uncalibrated fringe phase to com-

pute the calibrated baseband fringe phase. The PRECAL phase calibration algorithm is summarized below:

if (correlation cycle is valid):

for (each observation):

if (no a priori instrumental delay estimate for a given station is found in the station catalog):

repeat until (a priori instrumental delay estimate is acceptable)

- (1) Estimate station's instrumental delay in each channel for next correlator cycle.
- (2) Select individual channel delay estimate that best fits all channel's tone data for first correlator cycle as station a priori estimate.

for (each correlator cycle):

for (each station and channel):

- (3) Verify sufficient tone signals.
- (4) Resolve tone phase shift ambiguities against station a priori instrumental delay estimate.
- (5) Calculate instrumental delay from linear fit of tone phase shift against frequency spacing.

for (each channel):

- (6) Calculate stations' instrumental phases at each baseband fringe frequency.
- (7) Subtract difference in stations' instrumental phases at each baseband fringe frequency from corresponding baseband fringe phase.

Two additional operations are performed during data reformatting to ensure that the data organization is acceptable to PHASOR. PHASOR requires that any repeated observations of a given channel within a correlator cycle must be adjacent. However, every channel must be repeated in each cycle to obtain the multiple stopped tones needed for calibration, and some observations may use a cycle that repeats the same sequence of channels two or more times, e.g.,

1 2 3 4 5 6 1 2 3 4 5 6

Because of the nonadjacent repetition of channels, PRECAL factors cycles of this type into two or more cycles for the PHASOR program, e.g.,

1 2 3 4 5 6 / 1 2 3 4 5 6

The PHASOR program also requires all correlation intervals to have the same length. If they do not, PRECAL factors them

into uniform intervals equal to the greatest common divisor of the original lengths. For example, DSN clock synchronization scans typically use correlation intervals that are four times as long for the X-band channels (usually channels 4 through 6 at 8400-8440 MHz) as for the S-band channels (usually 1 through 3 at 2260-2300 MHz). Therefore, PRECAL factors each X-band interval of those scans into four shorter intervals and repeats the corresponding stopped fringe and tone data four times, transforming a cycle with variable length intervals such as

1 2 3 4 5 6

into an equivalent cycle with equal length intervals such as

1 2 3 4 4 4 4 5 5 5 5 6 6 6 6

## VII. BWS Ambiguity Resolution

The observed VLBI delay derived from the data in a single channel is called the bit stream alignment (BSA) delay or lag offset. Ideally, the residual BSA delays will be zero in all channels, when the data are correlated using perfect model parameters.

The precision with which the BSA delay can be estimated is limited by the effective bandwidth of the recorded signals. Because it is not practical to record an extremely wide-band channel, "bandwidth synthesis" is employed to extend the effective bandwidth. Data for bandwidth synthesis are obtained by recording a narrow-band channel and switching it rapidly over a wide range of channel frequencies. The phases for specified channel pairs are then combined into bandwidth synthesis (BWS) delays equal to the fringe phase difference divided by the difference in radio frequencies between the two channels. Bandwidth synthesis (BWS) delays provide the most accurate VLBI delay observations. BWS delays are ambiguous because they account for only the fractional phase differences between channels. Integer cycles of phase constitute a "delay ambiguity" equal to the reciprocal of the channel separation. By combining different pairs of channels to obtain varying separations, the ambiguities in the BWS delays may be resolved against the unambiguous BSA delay.

Since the same delay model is used for both BSA delays and BWS delays, they might be expected to have the same residuals. However, this will be true only for calibrated data. With uncalibrated data, instrumental delays severely corrupt the BWS delays and no meaningful comparisons between channel pairs for a single observation can be made. With calibrated data, the BWS delays represent the fractional part of the delay

residual after removal of an integer number of delay ambiguities. The delay ambiguity for each BWS channel pair in a band is the reciprocal of the channel pair separation, so we expect the BWS residuals to follow no particular pattern across pairs of channels. However, when the integer ambiguities are taken into account, the BSA delay residuals and all BWS residuals should agree to within their estimated errors.

An example of ambiguity resolution using calibrated data is shown in Table 1. The data are from observations of the radio source 4C 39.25 on the intercontinental baseline between the DSN 64-meter antennas located near Goldstone, California, and Canberra, Australia. Data in three S-band channels were calibrated using the PRECAL program and then were processed by the PHASOR program to obtain BSA and BWS delays. The mean of the three BSA delays is identified as channel 0 in Table 1. The ambiguities are resolved in order of increasing channel separation, starting with the narrowest channel pair, which is resolved against the mean BSA delay. The progressively smaller ambiguity in each ensuing channel pair is then resolved against the previous unambiguous BWS delay to obtain a sequence of increasingly accurate synthesized delay estimates. Successful resolution of the cycle ambiguities is indicated by agreement between successive channels to within the combined standard errors of the channels.

An independent verification of these results was obtained using the PCAL program to perform phase calibration on the uncalibrated fringe data. The calibrated delays obtained by this method were in agreement with the PRECAL results.

## VIII. Summary

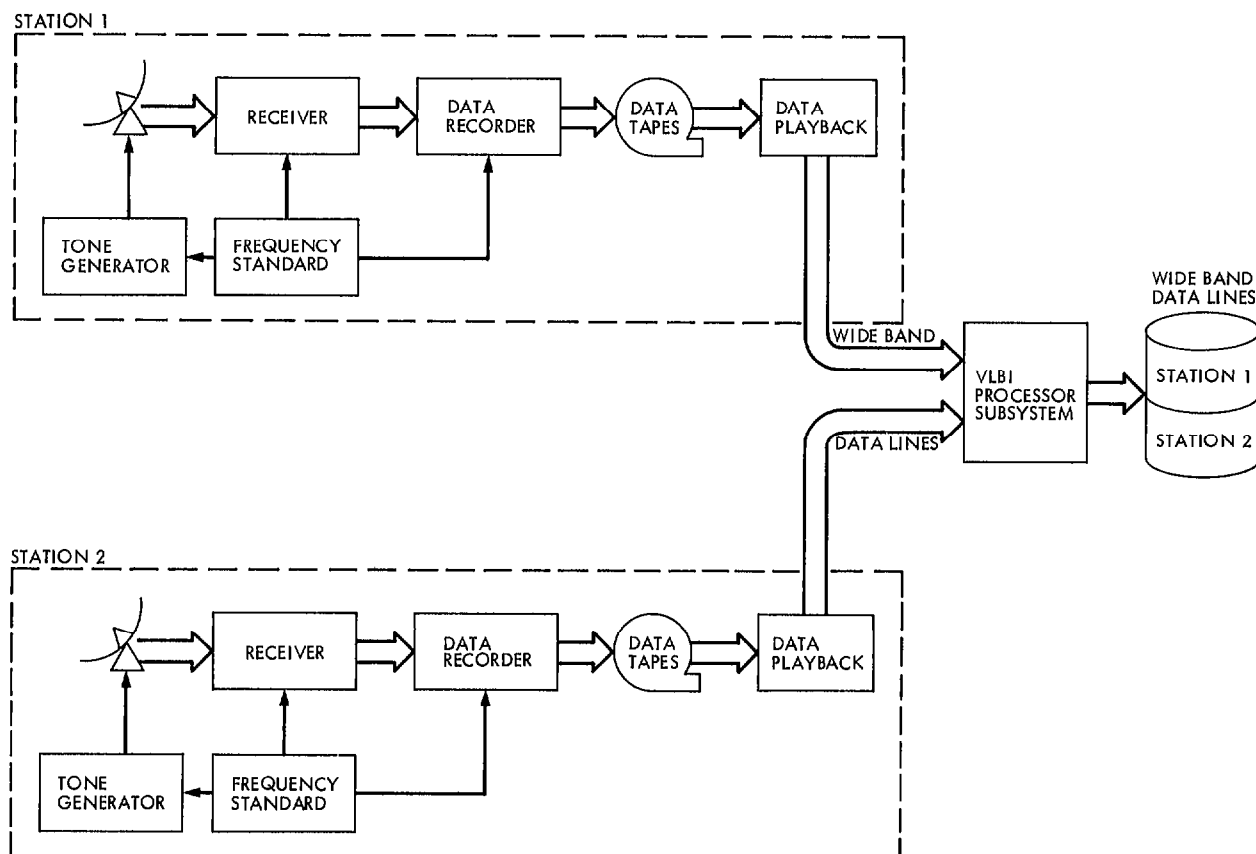
An improved method of calibrating instrumental delays is available for the DSN Block I VLBI System. This method uses the newly implemented PRECAL program to process phase-calibration tone data and combine them with the VLBI correlation sums prior to estimation of the delay parameters by the PHASOR program. Thus a substantial amount of additional processing that was previously required to extract the instrumental delay parameters and combine them with the PHASOR results is eliminated. Furthermore, the PRECAL program performs instrumental delay calibration over intervals as small as 0.4 sec, while the previous method performed only a single calibration for each channel over an entire observation. However, the full advantage of the new method cannot be realized until asynchronies between the recorder clocks and the phase calibration "clocks" are removed by the installation of new tone generator hardware (which is currently under development) at the DSN receiving stations.

## References

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3. Roth, M. G., "Intercontinental Synchronization of Atomic Clocks," Proceedings of the Precise Time and Time Interval Applications and Planning Meeting, 1981.
4. Thomas, J. B., *An Analysis of Radio Interferometry with the Block 0 System*, Publication 81-49, Jet Propulsion Laboratory, Pasadena, Calif., December 1981.
5. Software Specification Document: VLBI Processor Subsystem, Block I VLBI Correlation Operational Program, DSN Document SSD-NVV-5137-OP, Revision B.

**Table 1. Ambiguity resolution using calibrated BWS data**

	Channel			
	0	1	2	3
Bandwidth, MHz	0.25	7.000	32.750	39.750
Ambiguous delay, ns	—	29.483	−20.785	13.218
Nx ambiguity, ns	—	$30 \times 142.857$	$142 \times 30.534$	$171 \times 25.157$
Unambiguous delay (ns)	$4285 \pm 38$	$4315.19 \pm 0.83$	$4315.04 \pm 0.18$	$4315.06 \pm 0.16$



**Fig. 1. Overview of DSN Block I VLBI data acquisition system**



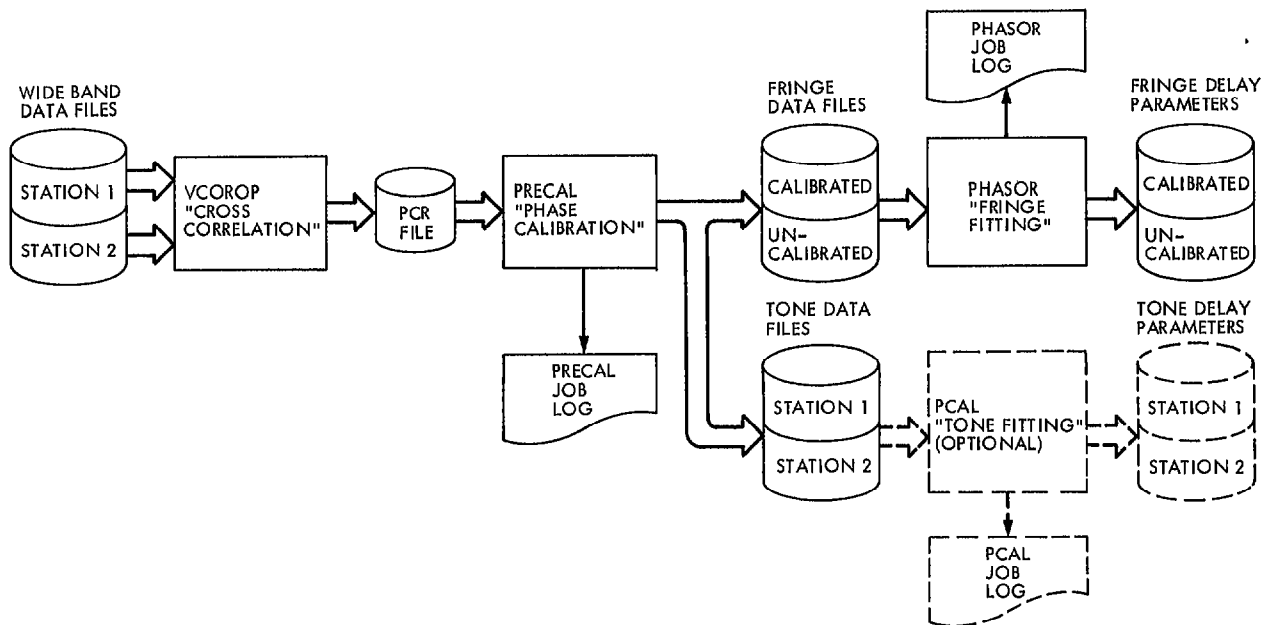


Fig. 2. Processing steps for phase calibration operation. Dashed symbols indicate optional functions for diagnostic purposes

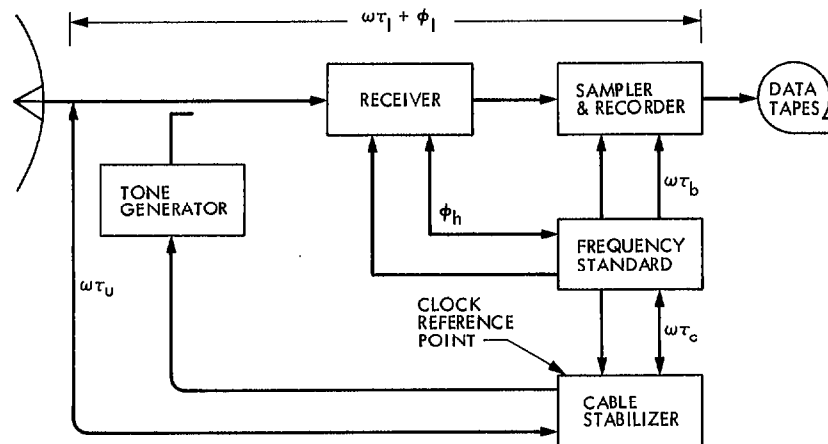


Fig. 3. Phase shifts experienced by a signal at frequency  $\omega$  passing through station instrumentation